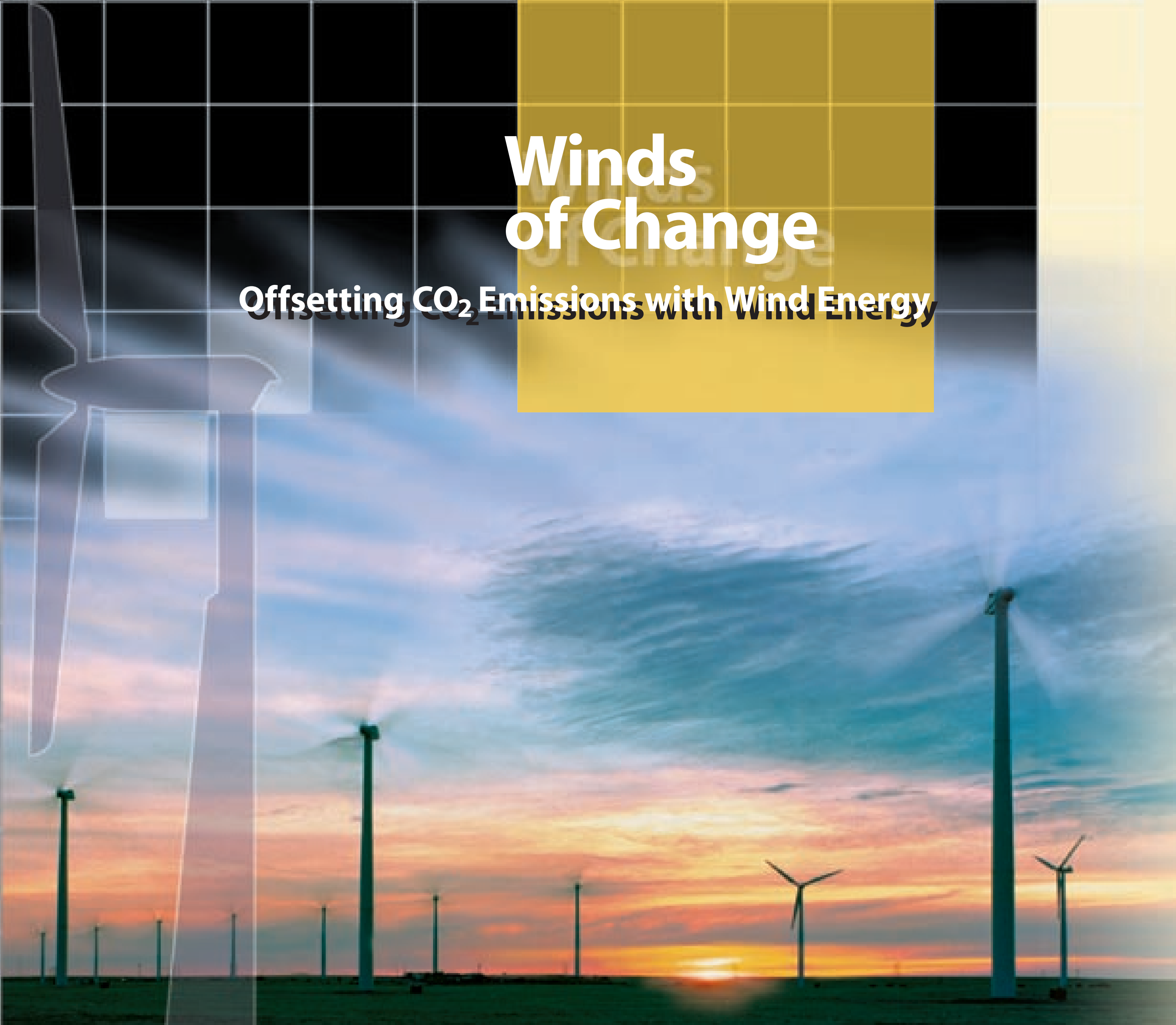
Winds of Change

Offsetting CO_2 Emissions with Wind Energy



"Climate change is occurring, " says John H. Marburger III, director of the White House Office of Science and Technology Policy. The Intergovernmental Panel on Climate Change (IPCC), a group of 2900 leading climate scientists from 120 countries, agrees. Climate change could lead to rising sea levels, ecological instability, and a growing incidence of weather anomalies such as floods and droughts — changes that are likely to have consequences for the world environment and economy.

IPCC scientists agree that climate change is the result of growing emissions of carbon dioxide (CO_2) and other greenhouse gases from anthropogenic (human) activities — deforestation, industrial processes, and fossil fuel combustion. As these gases accumulate in the atmosphere, they trap heat, creating a greenhouse effect.

Roughly 84% of the anthropogenic contribution to climate change is due to CO_2 ; the rest comes from gases such as methane, which traps 23 times more heat per gram of gas than CO_2, and nitrous oxide, which traps 296 times more heat. Even if all anthropogenic emissions were to stop tomorrow, the concentration of greenhouse gases in the atmosphere would take centuries to return to preindustrial levels. The IPCC has estimated that, to maintain stable atmospheric conditions in the long run, anthropogenic emissions of greenhouse gases must be cut 60% to 70%.

The United States itself produces about 23% of global greenhouse gas emissions. Plus, with a growing economy, U.S. emissions continue to increase at a rate of about 1% per year.

The Energy Connection

Most U.S. greenhouse gas emissions come from our reliance on fossil fuels, which are made up primarily of hydrogen and carbon. When burned, the carbon combines with oxygen to yield CO_2. In 2002, electricity production was responsible for 2249 Tg (teragrams, or million metric tons) of CO_2 emissions, or 39% of the U.S. total.

The U.S. government is considering ways to mitigate the problem, including voluntary measures to decrease U.S. greenhouse gas intensity — the ratio of emissions to economic output — by 18% during the next decade. In February 2003, speaking about the need to curb emissions, Energy Secretary Spencer Abraham said “We will also need to develop the revolutionary technologies to make these reductions happen. That means creating the kinds of technologies that . . . actually transform the way we produce and consume energy.”

Wind energy is such a breakthrough technology. Because wind power plants produce virtually no CO_2 emissions during operation, grid-connected wind power reduces overall greenhouse gas emissions by displacing the need for natural gas- and coal-fired generation.

The Wind Resource

Wind power is among the world’s fastest-growing sources of energy. In 2003, U.S.-installed wind generation grew by 1687 MW (greater than 30%) to 6374 MW. Worldwide, more than 8000 MW of wind capacity was added, bringing the international total to 39,000 MW.

The United States has enough wind resources to meet more than twice the nation’s total electricity demand. Wind resources are characterized by wind-power density classes, ranging from Class 1 (lowest) to Class 7 (highest). Fair to good wind resources (Class 3 and above), which have an average wind speed of at least 13 mph at a 50-m hub height, are found along the East Coast, the Appalachian Mountains, the Great Plains, the Pacific Northwest, and other areas. North Dakota alone has enough Class 4 and higher winds to supply a third of the electricity needs of the lower 48 states.

Using Wind Energy to Cut Emissions

Although a wind plant produces no CO_2 while generating electricity from wind, it does take fossil energy to mine, transport, and fabricate materials used in plant construction; build the power plant; operate and maintain the plant during its service life; and decommission the plant at the end of its useful life.

According to a 1989 DOE study, when all energy requirements are taken into account, a wind plant adds about 7.4 g of CO_2 to the atmosphere per kilowatt-hour of electricity generated. But this is lower than 964 g/kWh for a typical coal-fired plant, 484 g/kWh for a natural gas turbine plant, and 611.7 g/kWh generated by the average U.S. utility mix (which takes into account the electricity generated by a weighted mix of hydropower, nuclear power, coal, natural gas, and other generating technologies). Wind power thus can displace 956.6 g/kWh of CO_2 from coal plants, 476.6 g/kWh from natural gas plants, and 604.3 g/kWh of CO_2 from the average U.S. supply mix.

According to estimates by the DOE’s Energy Information Administration (EIA), total electricity demand will increase from 3839 billion kWh in 2002 to an estimated 5430 billion kWh in 2020. The great majority of this increase is expected to come from the use of new natural gas and coal-fired plants. A good portion of this increase is also expected to come from wind turbines. In fact, members of the wind energy industry project that wind-generated power will provide 6% or more of the nation’s electricity by 2020 (roughly 326 billion kWh). This would entail an average yearly growth rate of approximately 18%.

On the other hand, if the wind market grew at an annual rate of 28% (a growth rate that is less than that for the world market during the past five years), then in 2020 wind energy would provide approximately 20% of the nation’s electricity — which is often considered to be the maximum amount of wind energy that can be incorporated into the electricity grid without adversely affecting grid reliability (see also discussion on page 20). If wind has a 20% share of the electricity market in 2020, wind power plants will be generating about 1086 billion kWh; this would require roughly 413 GW of installed wind capacity, assuming an average capacity factor of 30% (see sidebar “Calculating Energy Output from Wind Turbines”).

Calculating Energy Output from Wind Turbines

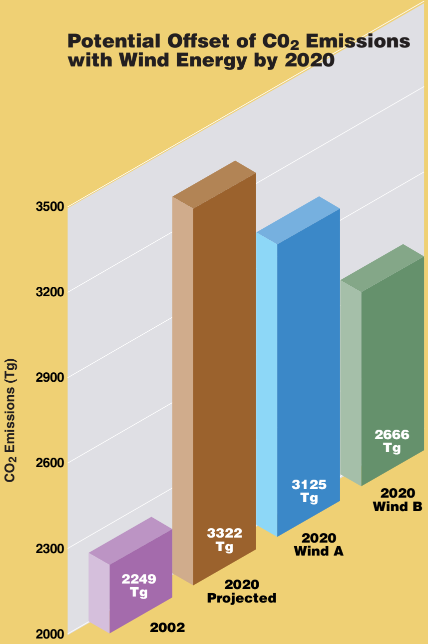
Wind turbines are usually classified according to their rated electric *power* output, e.g., 1 MW. This means the turbine can produce a maximum of 1 MW of power in ideal wind conditions. But because wind is an intermittent resource, the wind turbine won’t be operating at its maximum rated capacity all of the time. The average capacity at which the turbine operates during the course of its lifetime is called its capacity factor.

The question is how much electric *energy* (electricity) a wind turbine of a rated power output could produce over time. Energy production is usually determined by the equation: Energy = Power x Time. For electricity generating plants, this can be more accurately be restated as: Energy = Power x Time x Capacity Factor, where the capacity factor is the ratio of the amount of energy produced over time to the amount of energy that could have been produced if the turbine operated at its maximum rated output 100% of the time.

For example, with a capacity factor of 30% and 8760 hours in a year, the energy produced by a 1-MW wind turbine over the course of a year would be: 8760 h x 0.30 x 1 MW = 2628 MWh.

A turbine’s capacity factor is affected by the amount of down time required to service the turbine and by the site-specific wind conditions. The more time the turbine spends in service, and the lower the average wind speed at the site, the less energy the turbine produces, hence the lower the turbine’s capacity factor.

Capacity factors can vary widely. Today’s nationwide fleet of wind turbines is operating at an average capacity factor of 30%, and this ratio is improving. The American Wind Energy Association (AWEA) estimates that turbines installed since 2001 are operating at an average capacity factor of about 33%, and EIA estimates that, by 2020, some new turbines will be operating with capacity factors of 42% to 48%.



The EIA projects that CO_2 emissions from power plants could increase to 3322 Tg by 2020. But if wind energy supplied between 6% and 20% of the nation's electricity by then, the expected rise in CO_2 emissions would be reduced by 197 Tg (Wind A) to 656 Tg (Wind B), assuming that the wind energy would displace the average utility generation mix.

Using today's electricity supply mix and emission rates, CO_2 emissions from the electricity sector in 2020 would be about 3322 Tg, an increase of 1073 Tg. On the other hand, if wind energy could supply between 6% and 20% of the nation's electricity, wind would reduce the expected CO_2 emissions by between 197 Tg and 656 Tg — a significant impact under either scenario.

Getting There

A 6% market penetration of wind energy by 2020 not only appears to be an attainable growth scenario, but this amount of wind energy could easily be incorporated into the electricity grid despite an intermittent wind resource.

But how realistic is it to think that wind could provide 20% of the nation's electricity by 2020? In terms of achievable market growth, 20% is optimistic. In terms of resource, it could be accomplished without much difficulty — according to DOE, to provide 20% of America's electricity from wind, only 0.6% of the land of the lower 48 states would have to be developed with wind power plants. Much of the land could be used for a dual purpose — for both farming and wind energy, providing farms with an extra "cash crop."

What about intermittency? At deployment levels up to about 20%, wind power can be incorporated into the electricity grid relatively easily. The U.S. power grid already includes generating assets, such as hydroelectric power, that can be used to compensate for wind's intermittency. And wind forecasting software can overcome many of the challenges associated with intermittency.

According to Britta Buchholz of MVV Energie, German wind forecasters are currently able to predict wind strength and power output 48 hours ahead with 90% accuracy. As wind conditions can vary significantly from one place to another, the geographical disbursement of turbine arrays tends to decrease the variance in wind power output. This is because a drop in output from one wind farm can be made up by a rise from another.

Denmark, which gets about 17% of its electricity from wind, is starting to have some problems integrating wind power into its electricity grid. This is because Denmark is a small country that doesn't have enough geographical variability in wind patterns to even out fluctuations in wind strength (and hence turbine output). Small wind projects of single turbines or small clusters of turbines contribute the majority of Denmark's wind power.

If wind-generated electricity grows to comprise more than about 20% of power flows on the grid, the intermittency of the wind resource could pose a problem for grid system operators. Some form of backup generation (such as natural gas) or of energy storage would have to be used to compensate for wind's intermittency. Although exact data are not available, it is clear that this would degrade the energy payback ratio somewhat and would slightly increase emissions of CO_2. It is also likely that upgrades to the transmission infrastructure would be required for wind energy to service major load centers, although the cost of these improvements may not be prohibitive. NREL has estimated that 175 GW of wind capacity lie within 5 miles of existing 230 kV or lower transmission lines, and another 284 GW lie within 10 miles. In a series of letters to *Science* magazine in fall 2001, Stanford University researchers Mark Jacobson and Gilbert Masters concluded that, even assuming a relatively high average cost of $500,000 per mile to build new above-ground AC transmission lines, the cost of the new lines would add less than 1% to the cost of the wind

Reducing the Cost of Wind Energy

NREL is home to DOE's National Wind Technology Center (NWTC), where the main focus is to work with the wind industry to improve wind energy technology and decrease its cost. NWTC researchers are working with industry to develop new breeds of wind turbines that will operate efficiently in Class 3 and 4 wind regimes, with the goal to reduce costs for Class 4 areas to 3¢/kWh on land and 5¢/kWh offshore by 2012, and to reduce the cost of wind energy in Class 3 regimes to as little as 10¢/kWh by 2007.

One strategy for exploiting lower-class wind regimes is to develop advanced large turbines (1 MW or greater). Because they have a higher hub height where the wind typically blows stronger, and because larger blades are used to sweep greater areas, large turbines can harvest more energy for a given wind class. For these advanced concepts, researchers are considering every component — from the base of the tower to the tips of the blades — for opportunities to improve the technology.

They are, for example, researching blade sizes and shapes, and better and lighter materials with which to make blades and towers that last longer, extract more energy, and cost less to manufacture. They are investigating alternative concepts for drivetrain components (gearboxes, generators, and associated power electronics) that

Calculating the Energy Payback from Wind Turbines

Power plants consume energy even before they begin making it. Materials to be used in the plant must be mined, shipped, and fabricated; power plant parts must be transported to the construction site and assembled; the plant must be operated and maintained; and the plant must be disassembled and decommissioned at the end of its service life.

The time it takes for a power plant to generate as much energy as it uses over the course of its life is called the energy payback time. The energy payback of a power plant can also be expressed as the ratio of the energy generated by a power plant during its lifetime to the energy required to build, operate, and decommission the power plant.

According to European studies, a typical utility-scale wind turbine will produce, on average, 30 times more energy than it consumes during its lifetime. According to AWEA, a wind turbine's energy payback period is typically three to eight months, depending on the average wind speed at the site. Moreover, because energy payback is typically a measure of how long it takes to pay back fossil fuel energy, it is also a measure of how long it takes to pay back the CO_2 emitted by the consumption of that fossil fuel. In contrast, because they must consume fossil energy to produce electricity, fossil fuel power plants never achieve energy, or CO_2, payback.

power plants. (Note that their analysis assumes that existing transmission lines have room to carry the wind-generated power.)

What about the affordability of wind power?

According to DOE, new, utility-scale wind projects are being built in the United States today with energy costs ranging from about 3.9¢ to 7¢/kWh or more. The lower-cost wind energy is typically achieved for the better wind sites, such as Class 6. Wind energy at Class 4 sites, on the other hand, is currently marketed at prices in the 5¢ to 7¢/kWh range. In comparison, DOE's National Energy Technology Laboratory (NETL) reports that the average cost of electricity from current coal-generating facilities is 4¢/kWh and about 3.5¢/kWh from state-of-the-art facilities. NETL also projects that the cost of electricity from advanced coal facilities could be reduced to 3.1¢/kWh by 2010.

With the cost of wind power in the better wind regimes close to that of coal power, expanding the proportion of wind-generated electricity in the energy supply mix is not expected to have much of an impact on future electricity prices. A 2002 EIA study concluded that a federal renewables portfolio standard (RPS) requiring 10% of electricity to be generated from renewable sources by 2020 would result in a 1% increase in retail electricity prices, while a 20% RPS would result in a 3% increase. The study predicts that most new renewable electricity would come from wind, despite the fact that it assumes there will be no federal production tax credit for generation from wind plants and no renewable energy production incentive.

As researchers at NREL and in industry lower the costs even more, especially for wind turbines operating in Class 3 and 4 wind regimes, wind could become highly competitive with all other sources, and may even become the power of choice for many areas of the United States. If such becomes the case, wind energy could grow sufficiently to supply the United States with 20% of its electricity and could help the nation and the world find the means to decrease greenhouse gas emissions while meeting the energy needs of a growing economy. (See sidebar on "Reducing the Cost of Wind Energy.")

For More Information

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could result in less weight and more efficiency. And they are exploring new rotor designs to extract more energy from the wind and to reduce peak and fatigue loads.

NWTC researchers are also performing field and air-tunnel tests. They are using the results from the tests to develop computer simulations and models that will:

- **enable them to accurately project how wind turbines react to varying wind conditions;**
- **help them better forecast wind conditions and understand the characteristics and location of wind resources so that developers can site wind farms in the best locations; and**
- **allow them to predict the performance of advanced prototype designs, reducing development time and costs.**

The NWTC also provides world-class testing facilities. At the structural test facility, researchers can determine strength and durability of full-scale wind turbine blades. At the dynamometer facility researchers test the lifetime endurance of a wide range of wind turbine drivetrains and gearboxes at various speeds. Results from both facilities help turbine designers increase the lifetimes of blades and components by decreasing loads on the components, or making them more efficient and resistant to wear — thus increasing the life and reliability of wind turbine components and reducing costs.